Staged Magnetic Compression of FRC Targets to Fusion Conditions

ALPHA Annual Review

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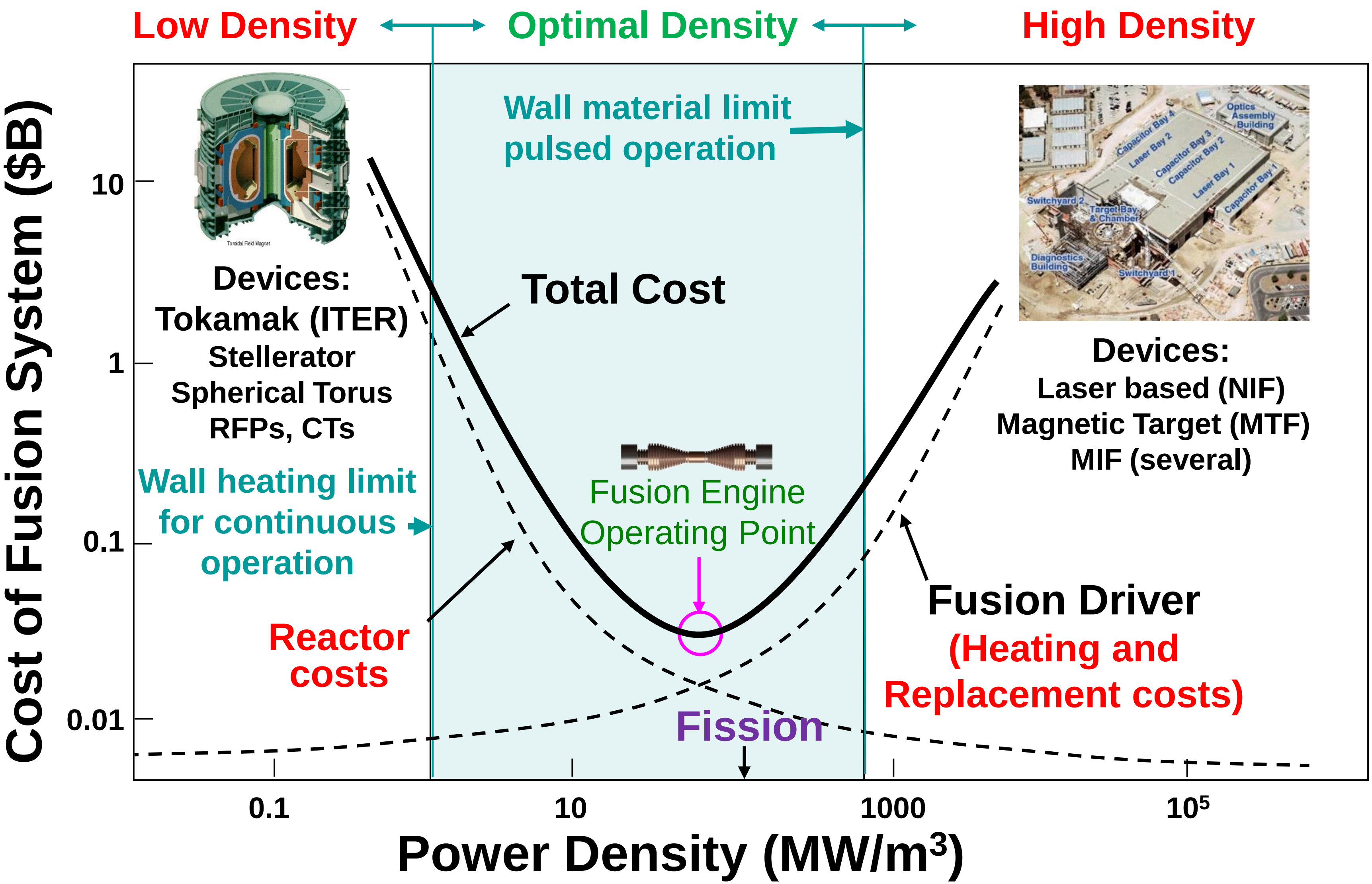
The Economics of Power Density

(Fusion's Goldilocks Zone)



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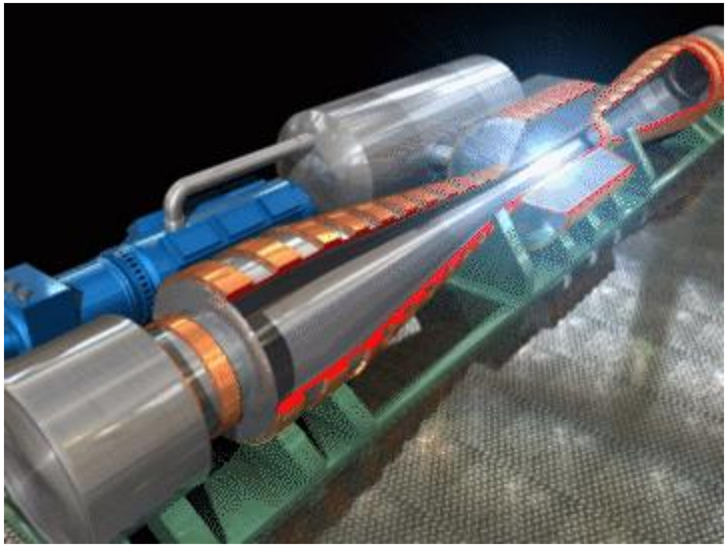
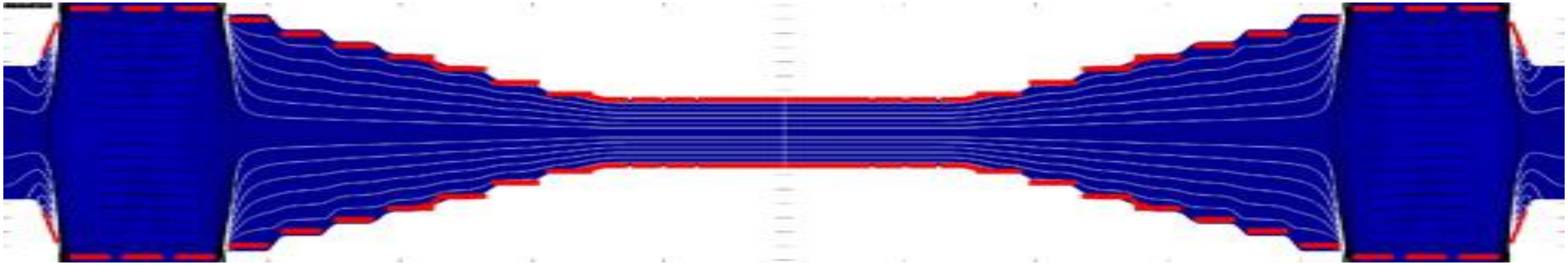
The Fusion Engine

1. **Dynamic Formation** – Two FRC plasmoids are dynamically formed by sequential field reversal
2. **Peristaltic Acceleration** – FRC plasmoids accelerated to high velocities (>300 km/s)
3. **Merging** –The two supersonic plasmoids merge converting FRC kinetic into ion thermal energy
4. **Adiabatic Compression** – FRC is reversibly compressed to fusion temperatures
5. **Energy Generation** – fusion neutron energy thermally converted in blanket with spent plasma and fusion ion energy directly converted to electricity



Artist's animation of the FE

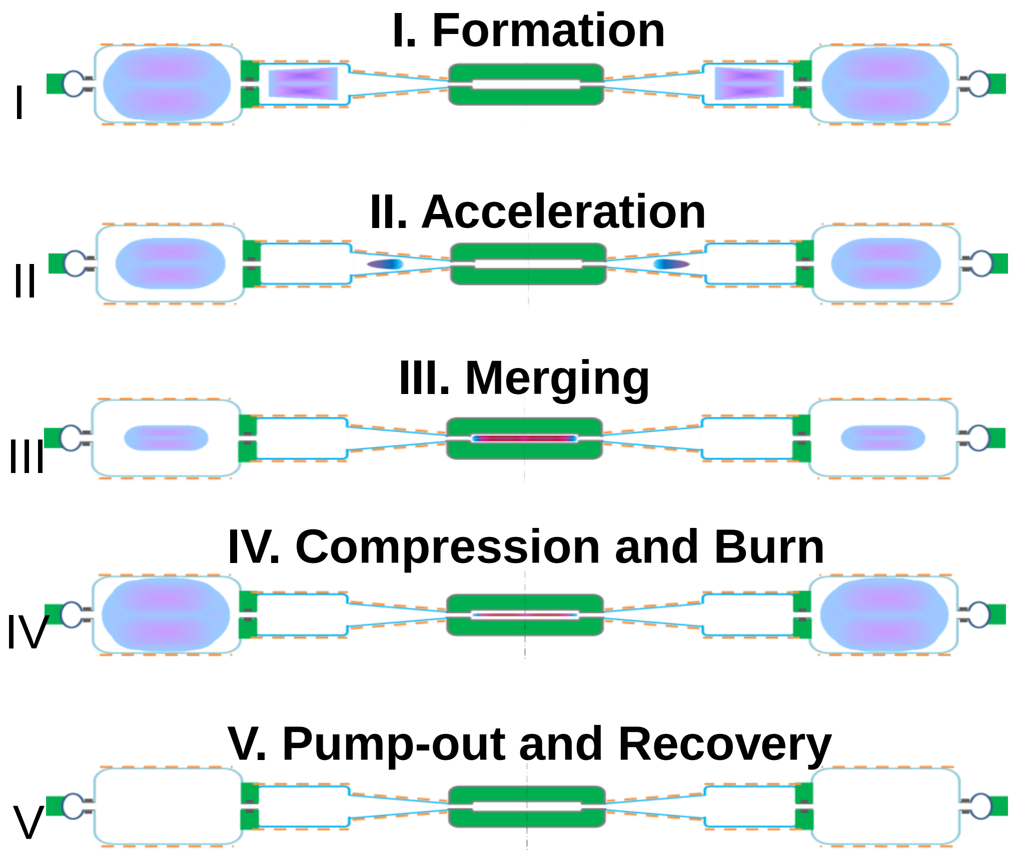


2D Magnetohydrodynamic simulation of the FE

Fusion Engine Electrical Energy Flow

Energy Input / Output (MJ)

	Comp	Accel	Form	Divertor
B^2			0.3	0.003
FRC			0.2	0.006
B^2		2.4	$0.3 \cdot \eta_e$	0.014
FRC		0.8		0.01
B^2	22.0	$2.4 \cdot \eta_e$		0.20
FRC	8.3			0.04
B^2	$22.0 \cdot \eta_e$			$0.33 \cdot \eta_e$
FRC	$2.0 \cdot \eta_{cdc}$			$7.3 \cdot \eta_{ddc}$
E_{neut}	$48.3 \cdot \eta_{th}$			
E_{He}	$2.0 \cdot \eta_{cdc}$			$7.0 \cdot \eta_{ddc}$
B^2				$0.09 \cdot \eta_e$
FRC				$0.18 \cdot \eta_{th}$
SUM	14.04	1.04	0.23	12.61



Net Electrical output per pulse: (26.65 – 1.27 – 0.29) = 25 MJ

= 50 MW_e @ 2 Hz

$\eta_e = 0.9$ $\eta_{cdc} = 0.7$ $\eta_{ddc} = 0.85$ $\eta_{th} = 0.45$

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Fusion Gain Scaling Based on Past FRC Confinement

$$E_{fus} \cong 1.2\times 10^{-12}\, n^2 \langle \sigma v\rangle\, \tau_N\, Vol_{FRC}$$

Collision cross section:

$$\langle \sigma v\rangle \cong 4\text{x}10^{-33}\, T_i^{2.6}(\text{eV})$$

Empirical FRC confinement scaling

$$\tau_N = 3.2\times 10^{-15}\, \varepsilon^{0.5}\, x_s^{0.8}\, r_s^{2.1}\, n^{0.6}$$

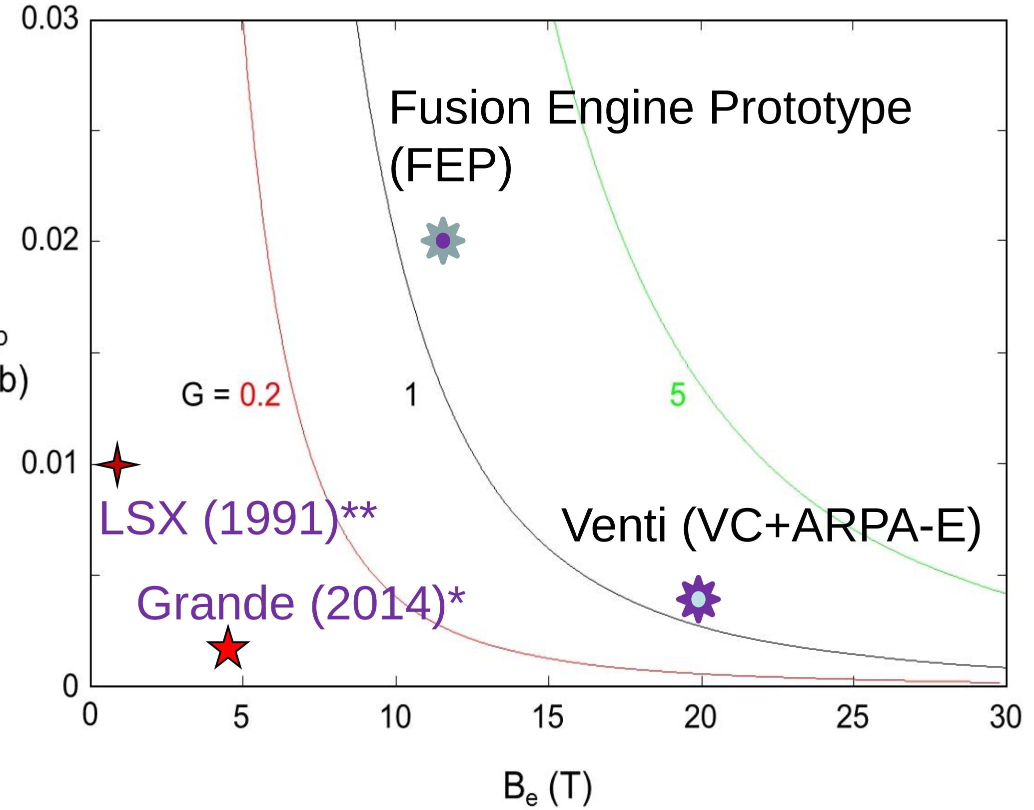
FRC energy:

$$E_{FRC} = \frac{3}{2} Nk(T_e + T_i)\cdot Vol_{FRC} \cong \frac{B_e^2}{2\mu_0}\pi r_s^2\, l_s$$

FRC internal (poloidal) flux:

$$\varphi_p \cong \frac{r_s^3}{r_c} B_e \quad \Rightarrow \quad r_s = \left(\frac{r_c\,\varphi_p}{B_e}\right)^{1/3}$$

$$G = \frac{E_{fus}}{E_{FRC}} = 0.093\, B_e^{2.4}\, \varphi_p^{0.82}\, l_s^{0.5}$$



Gain contours as a function of the FRC poloidal flux and compression magnetic field.
(FRC length l_s = 1 m)

* T_i ~ 4 keV l_s ~ 0.4 m ** T_i ~ 0.3 keV, l_s = 3 m

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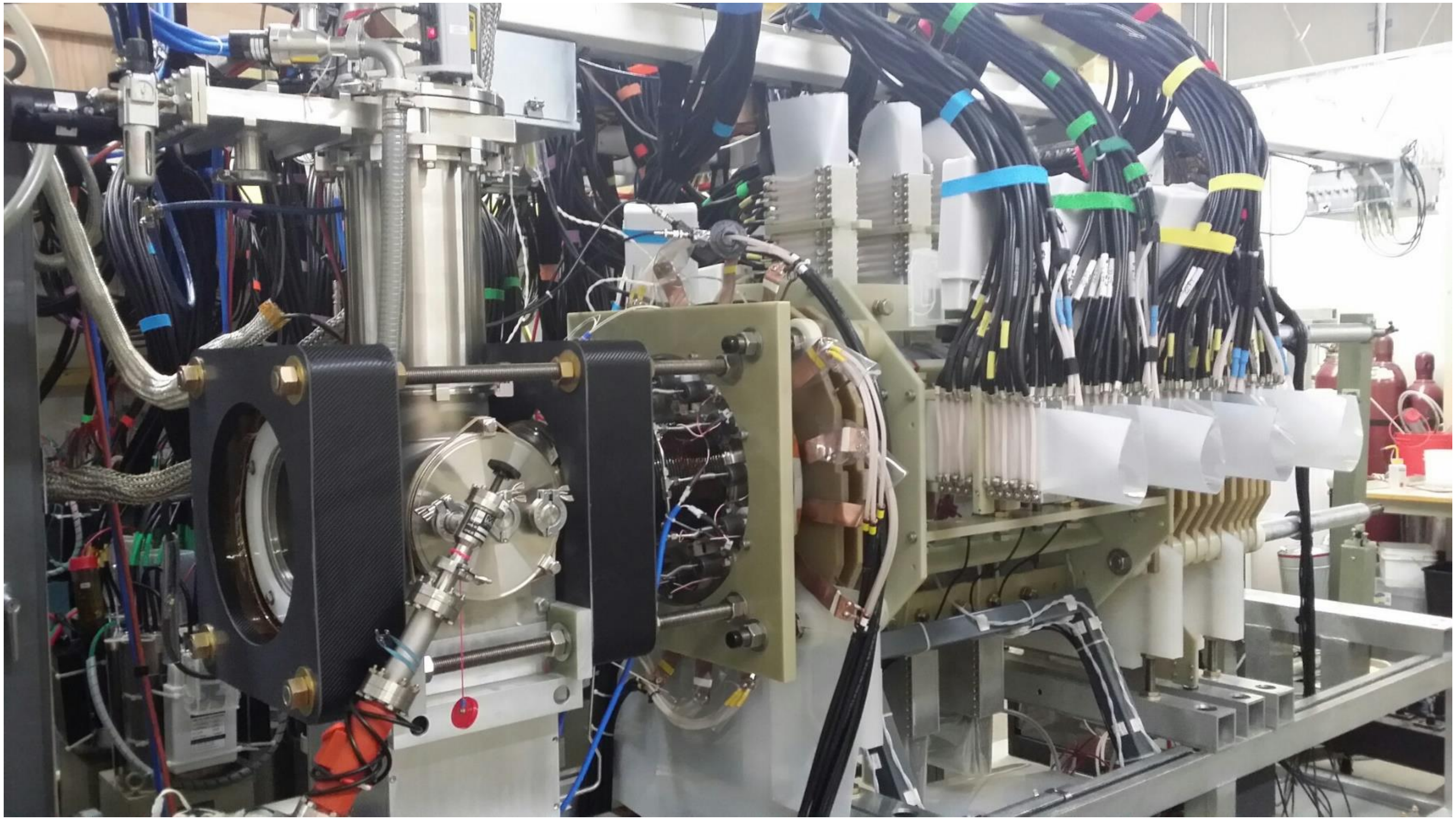
Current Experimental Effort

Completed Venti Formation Test Facility

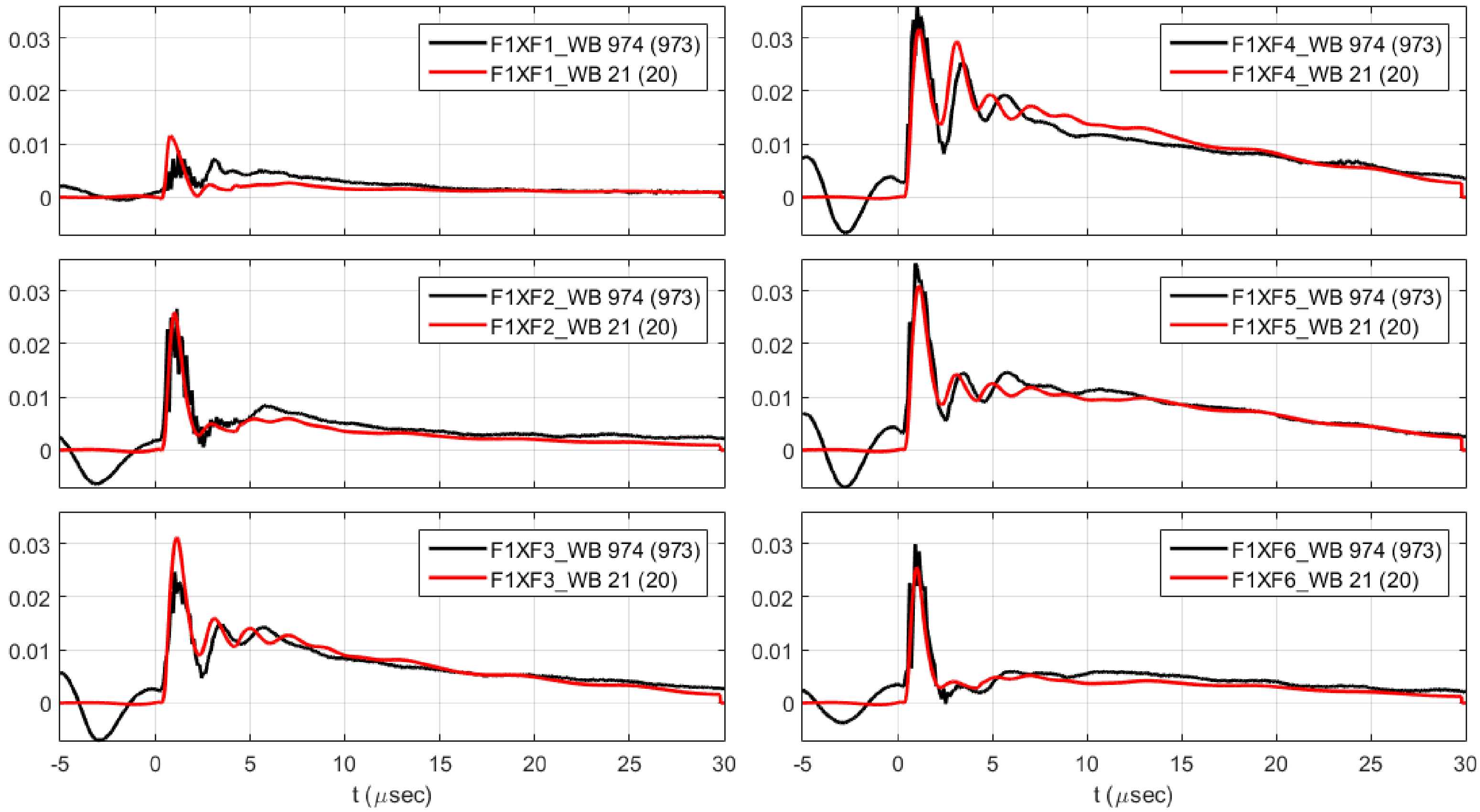


Current Theoretical Efforts

Recent Progress with Cygnus FRC code

- **Physics upgrades**
  - Modified pulse-power circuit(s)
  - "Free-slip" boundary conditions
  - Ohmic heating to ions
  - Ionization energy factor
- **Numerical upgrades**
  - r = 0 accuracy improvement
  - Increased accuracy/consistency of vacuum field solve
  - First multi-core operation (P-threads)
  - Direct calculation of mutual inductance matrix (circuit-centric)
- **Successful Benchmarking with Formation Experiment**
  - Vacuum shots compared with Venti-form data
  - PI shots compared with Venti-form data

Comparison of FRC Excluded Flux:
Experiment – disch. 974, Simulation – calc. 21



Cygnus Development Vision

R	2D MHD + Circuits + Physics “Cygnus_red”
O	Version Red + Hall + Bias
Y	3D (Version Orange + Fourier toroidal ∠)
G	3D Version Orange + test particles
B	3D w. self-consistent particles
I	3D particles w. noise reduction
W	Final 3D version

Current code

Energy Generation from Fusion at a Fraction of the Cost and Time

Technology Summary

- Power density scales as $\beta^2 B^4$ - the Fusion Engine will operate at the highest β and steady B of all fusion plasmas
- Cylindrical geometry with external exhaust thereby solving blanket and divertor materials issues
- Staged compression and magnetic energy recovery assure high electrical efficiency and rapid pulse repetition rates

Technology Impact

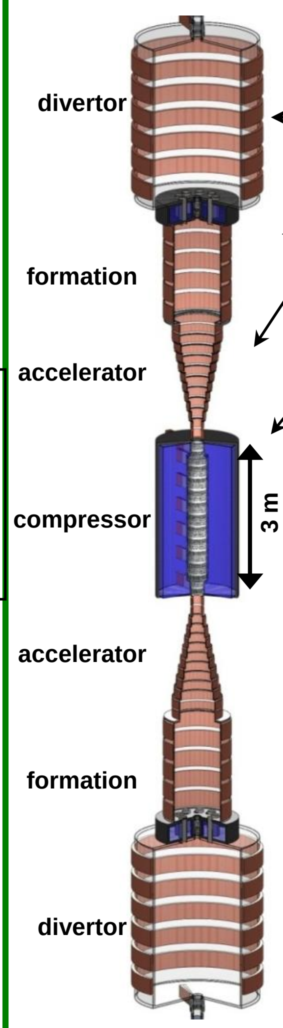
- Scale and complexity of fusion reactor greatly reduced
- Fusion Engine Prototype will demonstrate multi-keV ions, densities up to 10^{24} m^{-3}, with the potential for breakeven

Proposed Targets

Metric	State of the Art - NIF	Fusion Engine Prototype
Facility & Op. Cost ($)	> 5 Billion	0.008 Billion
Time to full power operation	15 yrs	< 2 yrs
η_d (=E_{plasma} /E_{spent}) · Gain *With mag. energy recovery η=0.7	5×10^{-5} ·1.5	0.2*·1.2
Rep Rate (shots/month)	20	2000

Fusion Engine

50 MW_e @ 2Hz

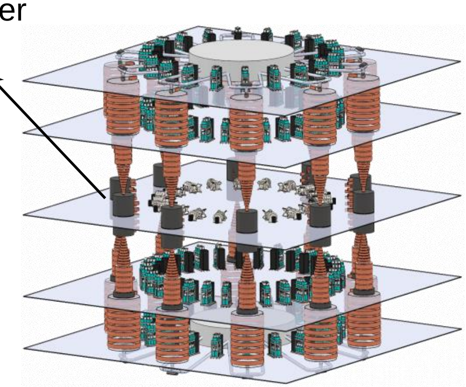


Large external divertor: mitigates power loading and provides for exhaust plasma energy recovery at high thermodynamic efficiency.

Magneto-kinetic accel/compression: direct, high efficiency ion heating to fusion temperature

Remote burn: ideal breeding geometry. Flowing heat exchanger solves Tritium breeding issues

Modular reactor design: lower cost, risk, greater availability, flexible siting, on-demand & base load power



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